# Polarization and modal field properties of quinquangular-core photonic crystal fibers

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A kind of highly birefringent quinquangular-core photonic crystal fiber (Q-PCF) structure is proposed and analyzed by full-vector finite element method (FEM). The modal field, effective index, and birefringence properties are investigated. From the numerical results, it is found that the birefringence of the new polarization-maintaining PCFs is at least five times larger than that of the standard highly birefringent hexagonal PCFs (H-PCFs) with the same hole pitch, hole diameter, and whole hole area as that of the new PCFs at 1 550 nm. Moreover, the modal field of the new PCFs could be better restricted than that of the standard highly birefringent H-PCFs; hence, the loss of fibers could be reduced.

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Photonic crystal fibers (PCFs), also known as "holey fibers", are micro-structured fibers[1] where arrays of holes run along the waveguide length of the fibers[2]. PCFs have significant applications[3,4] for a range of waveguiding applications due to the advantages arising from their modal properties, which are strongly dependent on their geometrical parameters[5] and their flexible structures. We can provide a wide degree of freedom (DoF) for PCFs by changing the geometric characteristics of the cross section of fibers. Using PCFs, highly birefringent fibers can be easily realized because the index contrast is higher than conventional fibers and the fabrication process permits the formation of the required microstructure near the fiber core[6]. The modal birefringence of conventional polarization-maintaining fibers (PMFs) are found in the order of $5\times10^{-4}$, but the birefringence of polarization-maintaining PCFs (PM-PCFs) is reported to be in the order of $10^{-3}$, the magnitude of which is one order higher than that of conventional PMFs[7]. The development and application of PCFs have provided great foreground for the research of fiber optical gyroscope (FOG). Compared with normal FOG, photonic crystal FOG is prone to achieve miniaturization and high degree of accuracy.

In this letter, a new kind of highly birefringent PCF structure with five air holes in the first ring is proposed, which is called quinquangular-core PM-PCFs (Q-PM-PCFs). The modal field, effective indices, and birefringent characteristics are analyzed by using the full-vector finite element method (FEM). Our analysis shows that the modal field of the new PM-PCFs can be commendably restricted. In addition, its birefringence can easily achieve the order of $3.7\times10^{-3}$ at 1 550 nm compared with the value of the standard highly birefringent hexagonal PCFs (H-PCFs) of only $6.9\times10^{-4}$, which strongly proves that the proposed structure is highly polarized. Additionally, the modal field of the new PCFs could be better restricted. For this reason, the loss of fibers can be effectively reduced.

PM-PCFs could be realized by changing the geometric characteristics of the cross section. The fabrication of PM-PCFs can use two different air hole diameters along two orthogonal axes near the core region, which provides the effective index difference between two orthogonal polarization modes[8]. In this letter, the Q-PM-PCFs were obtained by enlarging three air holes in the first ring of the Q-PCFs, which were proposed and analyzed in Ref. [9]. The structure of the Q-PM-PCFs is shown in Fig. 1, in which the smaller air hole diameter $d_1 = 1$ $\mu$m, the larger air hole diameter $d_2 = 2$ $\mu$m, and the hole pitch $\Lambda = 2$ $\mu$m.

At present, the modal solution approach based on the FEM is more flexible than other approaches as it matches well to the complex structure of PCFs[10]. Based on the full-vectorial **E** field-based FEM, the characteristics of the Q-PM-PCFs shown in Fig. 1 and the standard highly birefringent H-PCFs with the same hole pitch, hole diameter, and whole hole area as that of Q-PM-PCFs are analyzed.

The modal field profile and its spot size depend on the refractive index distribution across the optical waveguide cross section[11]. We obtained the modal field profiles of the Q-PM-PCFs and the standard highly birefringent H-PCFs at the wavelength of 1 550 nm, as shown in Figs. 2 and 3, respectively. The field can penetrate the

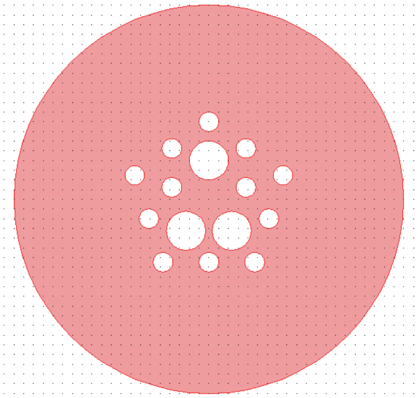

Fig. 1. Geometries of Q-PM-PCFs.

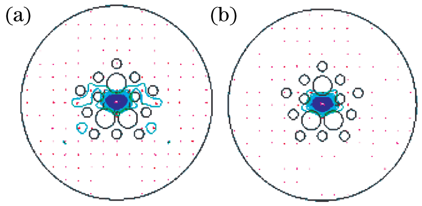

Fig. 2. Modal field profile of the (a) $x$-polarization mode and (b) $y$-polarization mode of the Q-PM-PCFs at 1 550 nm.

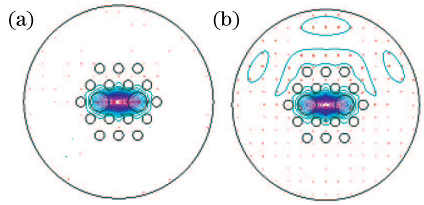

Fig. 3. Modal field profile of the (a) $x$-polarization mode and (b) $y$-polarization mode of standard highly birefringent H-PCFs at 1 550 nm.

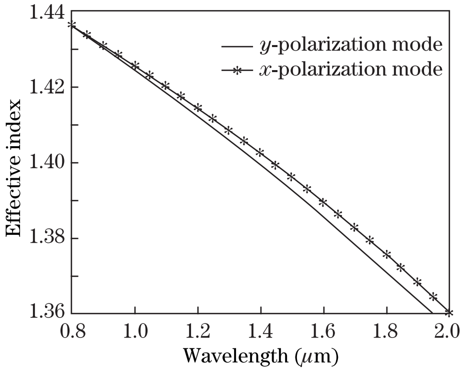

Fig. 4. Effective index curves of two orthogonal polarization modes as a function of wavelength, where Q-PM-PCFs $\Lambda = 2$ $\mu$m, $d_1 = 1$ $\mu$m, and $d_2 = 2$ $\mu$m.

lattice near the center of the fibers, but it dies out after a few holes. It can be observed that the $x$-polarization modal field expands larger than the $y$-polarization modal field at the same wavelength. The $x$-polarization mode has the characters of transverse electric (TE) mode, the effective index of which is slightly higher than that of the $y$-polarization mode, because its modal field extends into the air hole cladding region more than that of the $y$-polarization mode. It can also be observed that the modal field of the Q-PM-PCFs can be well restricted. In the Q-PM-PCFs, the field expansion is much smaller than that of the standard highly birefringent H-PCFs at the same wavelength. The well-restricted modal field of the new PCFs due to increased index difference[11] caused the optical energy to mainly transmit in the core of the fibers, thus the loss of fibers was maximally reduced.

The effective index curves of the $x$-polarization and $y$-polarization modes as a function of operating wavelength are shown in Fig. 4. Both values reduce monotonically with increasing operating wavelength $\lambda$, and the effective value indices of the $y$-polarization modes are higher than that of the $x$-polarization modes at the same wavelength.

The effective index curves of the $x$-polarization and $y$-polarization modes as a function of large air hole diameter $d_2$ are shown in Fig. 5. At wavelength of 1 550 nm, both values reduce monotonically with increasing large air hole diameter $d_2$, which varied by ~0.5 $\mu$m. As the hole diameter is increased, the equivalent index of the air hole cladding region is reduced[2]. In addition, the equivalent indices of the $y$-polarization modes are higher than those of the $x$-polarization modes at the same wavelength.

PCFs are usually fabricated from a single material (fused silica). Therefore, the birefringence of the PCFs is attributed mainly to geometric anisotropy[12]. The birefringence curves of the Q-PM-PCFs and the standard highly birefringent H-PCFs as a function of operating wavelength are shown in Fig. 6. It can be observed that the birefringence of Q-PM-PCFs is higher than that of the standard highly birefringent H-PCFs, particularly in the wavelength range of 1.4–1.8 $\mu$m. At the wavelength of 1 550 nm, the birefringence of Q-PM-PCFs is $3.7\times10^{-3}$, whereas the value of the standard highly birefringent H-PCFs is only $6.9\times10^{-4}$. From the numerical results, it is confirmed that the Q-PM-PCFs we proposed are highly polarized.

Moreover, a wide DoF for the birefringence of Q-PM-PCFs could be obtained by changing the geometric characteristics of the cross section of the fibers, e.g., large air hole diameter $d_2$, which is shown in Fig. 7. It can be observed that the birefringence increases monotonically with the increasing large air hole diameter $d_2$, which varied from 1.2 to 2.4 $\mu$m. This is because higher $d_2$ diameter causes the Q-PM-PCFs structure to be more

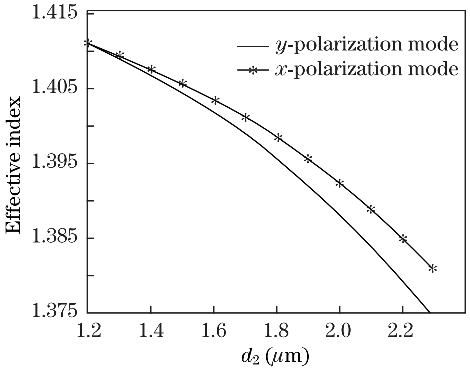

Fig. 5. Effective index curves of two orthogonal polarization modes as a function of large air hole diameter $d_2$, where Q-PM-PCFs, $\lambda = 1.55$ $\mu$m, $d_1 = 1$ $\mu$m, and $d_2 = 2$ $\mu$m.

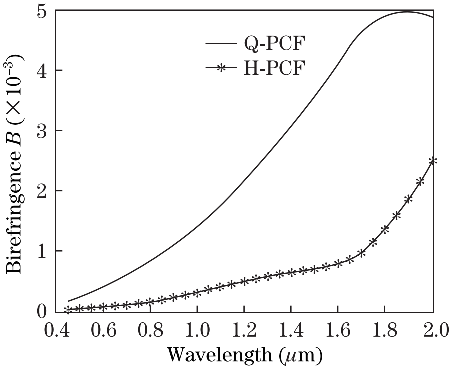

Fig. 6. Birefringence curves as a function of wavelength.

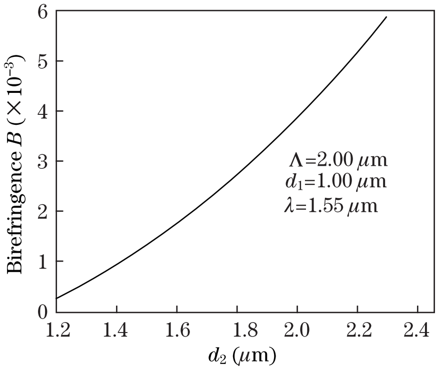

Fig. 7. Birefringence curve of Q-PM-PCFs as a function of large air hole diameter $d_2$.

asymmetric.

In conclusion, a new kind of highly birefringent PCF structure with five air holes in the first ring is proposed. The modal field, effective indices, and birefringence properties are calculated. The birefringence of the new PM-PCFs can achieve $3.7\times10^{-3}$ at 1 550 nm, which strongly proves that the proposed structure is highly polarized. In addition, the modal field of the new highly birefringent PCFs can be well restricted. It is very important for sensing applications, e.g., FOG. To improve applications, we will further analyze and research the new highly birefringent PCFs (Q-PM-PCFs) in future studies.

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